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Effect of Mn and Al contents on hot ductility of high alloy Fe-xMn-C-yAl austenite TWIP steels

Hongbo Liu[a,*], Jianhua Liu[a,*], Bowei Wu[a], Yaozu Shen[a,b], Yang He[a], Hao Ding[a], Xiaofeng Su[a,c]

[a] Institute of Engineering Technology, University of Science and Technology Beijing, Beijing 100083, China
[b] School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, China
[c] Technical Center, Hebei Xinji Aosen Steel Co.Ltd., Xinji 052360, China

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ABSTRACT

Effect of Mn (14.94,18.21, and 23.6 wt%) and Al (0.002,0.75, and 1.47 wt%) contents on hot ductility of five high alloy Fe-xMn-C-yAl austenitic Twinning induced plasticity (TWIP) steels were investigated by Gleeble-3500 thermo-mechanical simulator in the temperature range 700–1200 °C under a constant strain rate of $3 \times 10^{-3}\ s^{-1}$. The results indicated that the hot ductility of different Mn-containing TWIP steels are not appreciable with all the reduction of area (RAs) values lower than 30%, and RAs would be further decreased as the Mn content increased. The matrix of TWIP steel is inhomogeneous with severe Mn microsegregation in the interdendritic zone. Moreover, the C microsegregation ratio increases from 0.85 to 1.16, 0.76–1.22, to 0.74–1.32 when Mn concentration increases from 14.94 wt%, 18.21 wt%, to 23.6 wt%, respectively. Additionally, the microstructure and the true stress-true strain curves suggested that dynamic recrystallization (DRX) took place in 14.94 wt% Mn bearing TWIP steel, while the fraction of DRX grains decreased dramatically with increasing Mn content. Therefore, it is inferred that the high Mn addition inhibited DRX, together with the acceleration effect of C microsegregation by Mn addition should be the most predominant factor of the hot ductility loss with Mn content increases in TWIP steels. On the other hand, Al addition to TWIP steels resulted in a dramatic increase of AlN particles content. The AlN particle accounted for nearly 64% of the total precipitate content for the 1.59 wt % Al containing TWIP steel. Compared with Al-free TWIP steel, the excessive number of fine AlN particles in the 1.59 wt% Al containing steel effectively pinned the austenite grain boundaries, which inhibited the occurrence of DRX and simultaneously promote grain boundary sliding, resulting in the deterioration of hot ductility.

1. Introduction

Twinning Induced Plasticity (TWIP) steels are being developed for automobile during the last decade, attributed to its combination of very high strength and ductility at room temperature [1–6]. The microstructure of TWIP steels are fully austenitic since they are in the FCC phase, and twins would be formed in profusion under plastic deformation [7,8]. The twins could refine the grain size and hinder dislocation motion during deformation, and in consequence improve the strength of TWIP steel [9–12]. Furthermore, these twins would cause a high degree of strain hardening and thus the ductility of TWIP steel is enhanced [13]. According to the previous studies, the tensile strength and elongation of TWIP steels could reach up to 1200 MPa and 90pct, respectively [14,15]. Therefore, the formation of twins when TWIP steel is deformed is a perfect fit for parts on a car intended to absorb energy on impact.

It is generally accepted that the detonation of mechanical twinning would occur when the stacking fault energy (SFE) is low ($18 \le SFE \le 45\ mJ/m^2$) [16–18], and the SFE value is largely affected by the contents of alloying elements [19]. In order to make twinning the dominant deformation mechanism, a high manganese content of about 15–30 wt % is needed to be alloyed into TWIP steel [20]. Additionally, Cho et al. [21] found that Al element is a favorable addition, as it could effectively suppresses the hydrogen delayed [22–24], and cementite precipitation [25–27] in Fe-Mn-C TWIP steel.

However, the additions of such high percent of Mn and Al in TWIP steels have posed challenges to casting and rolling processes [28]. Generally, the continuous casting slab is casted in a mold and has to be straightened at some stage in the conventional continuous casting process. In the straightening operation, the surface of steel is hot tensioned at 700–950 °C, and deformed at certain strain rates in the range of 10^{-3} to $10^{-4}\ s^{-1}$, where most steels present poor ductility. As a consequence, some continuous casting defects, like transverse cracks, would be easily formed in steel. Also, Wang et al. [29] reported that the

* Correspondence to: University of Science and Technology Beijing, Room 809, keji Building, NO. 30 Xueyuan Road, Haidian District, Beijing 100083, China.
E-mail addresses: ustbliuhongbo@163.com (H. Liu), liujianhua@metall.ustb.edu.cn (J. Liu).

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Table 1
Chemical composition (in mass pct) of the present steels.

Steel	C	Mn	P	S	Al	N	O
15Mn1.5Al	0.66	14.94	0.0072	0.0082	1.46	0.0088	< 0.0005
18Mn1.5Al	0.64	18.21	–	0.0076	1.59	0.0078	< 0.0005
23Mn1.5Al	0.66	23.60	–	0.0080	1.40	0.0092	< 0.0005
18Mn0Al	0.61	18.22	–	0.0071	0.002	0.010	0.0010
18Mn0.75Al	0.61	17.70	–	0.0078	0.75	0.0087	< 0.0005

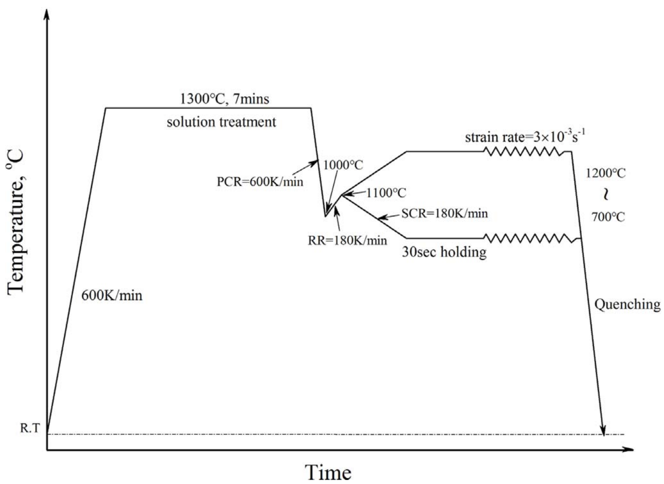

Fig. 1. Schematic diagram of testing conditions for tensile specimens. Symbols and process are described in the text.

sensitivity to surface cracking of TWIP steel is extremely high, which led to the increase the cost of production. Evaluation of steel sensitivity to cracking is usually carried out by hot tensile tests, which shows the reduction of area (RA) of tensile specimens as a function of temperature.

It is worth noting that until the present time, there are limited literatures available concerning the hot ductility behavior of as cast TWIP steels [28–33]. Generally, the results of these research work showed that the RA of TWIP steels in tensile tests was all lower than 40% in the temperature range of 700–1100 °C. And, Lan et al. [28] suggested that the high Mn content in Fe-22Mn-0.6 C TWIP steel caused inevitably Mn microsegregation and microporosity in as cast structure. This reduced the matrix homogeneity of the TWIP steels and thus led to the decrease of hot ductility. In Cabanas and Akdut's research [30], the addition of Mn delayed the dynamic recrystallization in Fe-Mn binary alloys. Similarly, Hamada et al. [31] revealed that high Mn contents would delay significantly the static recrystallization rate in TWIP steels. On the other hand, Kang et al. [32,33] have investigated the hot ductility of TWIP steel. And, their important finding was that the MnS particles appear to act as nucleation sites for the precipitation of AlN, and the primary and secondary AlN precipitates could be detected on prior austenite grain boundaries, leading to the decrease of hot ductility. However, most of the above studies only focused on TWIP steel with single component and didn't investigate the effects of Mn and Al content on the hot ductility. Also, there existed some divergences concerning the mechanisms of hot ductility of TWIP steel. Thus, more efforts are needed to study high temperature tensile behaviors of TWIP steel. The aim of present work is to get a clear understanding of the effect of Mn and Al contents on the hot ductility of TWIP steels. Besides, the related factors influencing the deformation mechanism, such as phase transformation, matrix homogeneity, facture behavior, precipitated particles, and the occurrence of DRX, were discussed.

2. Materials and methods

Five high alloy Fe-Mn-C-Al austenite TWIP steels whose nominal chemical compositions are 15Mn-0.6C-1.5Al, 18Mn-0.6C-1.5Al, 23Mn-0.6C-1.5Al, 18Mn-0.6C-0Al, 18Mn-0.6C-0.75Al were fabricated in the 50 kg capacity vacuum induction furnace in Institute of Engineering Technology of USTB, China. The measured chemical composition of TWIP steels are specified in Table 1. It should be noted that the Mn content was measured through perchloric acid oxidation trivalent manganese titrimetric method, the Al content was analyzed by ICP emission spectrometry, and the concentrations of C and S elements were measured by infrared absorptiometry method after combustion. Besides, the insert gas fusion-infrared absorptiometry was used to measure the O and N contents in TWIP steels based on ASTME11019-2011 ASTM standard.

Tensile specimens with a cylindrical shape were cut from the dendrite grain zone, the length and diameter of which are 120 mm and 10 mm, respectively. Hot tensile tests were conducted using Gleeble-3500 thermomechanical simulator in the testing temperature range of 700–1200 °C. It is worth noting that the heating unit of Gleeble-3500 was flooded with argon to protect the specimens from oxidation. The thermomechanical cycle (see Fig. 1) used in the present study was as follows. First, the specimens were heated from room temperature to 1300 °C at 600 K/min, and held for 420 s. The specimens were directly cooled down to 1000 °C at a primary cooling rate (PCR) of 600 K/min, followed by a reheating operation to 1100 °C at a reheating rate (RR) of 180 K/min. Then, the specimens were cooled at a secondary cooling rate (SCR) of 600 K/min to each testing temperature with an interval of 100 °C in the temperature rang 700–1200 °C. Once the specimens had reached the test temperature, they were held for 30 s before straining to

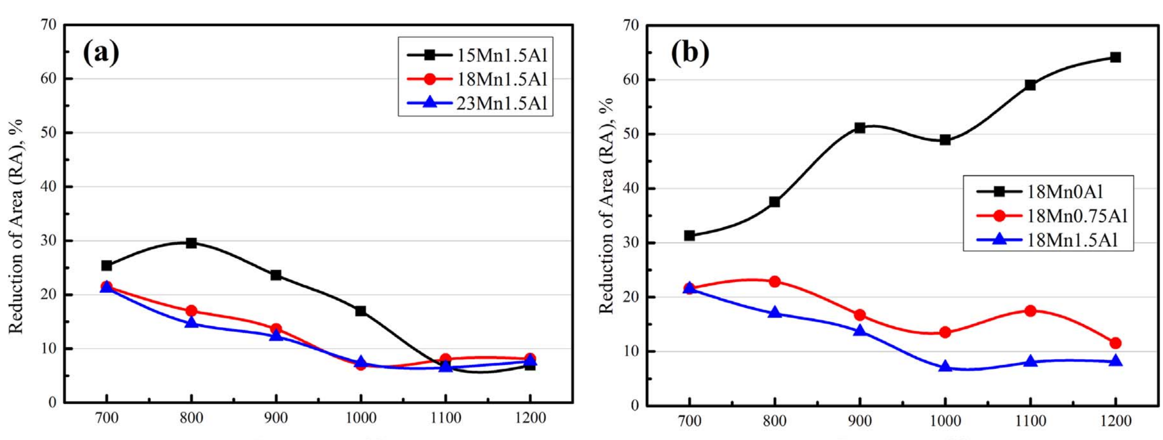

Fig. 2. Hot ductility curves of the investigated TWIP steels as a function of temperature. (a) Influence of Mn on hot ductility, (b) Influence of Al on hot ductility.